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GIS METHODOLOGY FOR QUANTIFYING CHANNEL CHANGE IN LAS VEGAS, NEVADA[1]

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ABSTRACT: This study applies spatial analyses to examine the consequences of accelerated urban expansion on a hydrologic system over a period of 24 years. Three sets of historical aerial photos are used in a GIS analysis to document the geomorphic history of Las Vegas Wash, which drains the rapidly growing Las Vegas urban area in southern Nevada. New spatial techniques are introduced to make quantitative measurements of the erosion at three specific time intervals in the hydrologic evolution of the channel and floodplain. Unlike other erosion studies that use two different elevation surfaces to assess erosion, this study used a single elevation surface to remove systematic and nonsystemic elevation errors. The spatial analysis quantifies channel changes for discrete time periods, calculates erosion volumes, and provides a foundation to examine how the specific mechanisms related to urban expansion have affected Las Vegas Wash. The erosion calculated over 24 years is the largest documented sediment loss attributed to the effect of rapid urban growth.

(KEY TERMS: urban erosion; geospatial analysis; time series analysis; land cover change; sediment erosion calculation; channel evolution.)

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INTRODUCTION

In the face of significant population growth in urban centers, changes in urban hydrologic systems have received increasing attention among geomorphologists, hydrologists, ecologists, and civil engineers (e.g., Geomorphology volume 79; this volume). Over the past century urban sprawl has transformed farmland, forested areas, deserts, and wetlands to impervious surfaces; and urban streams have experienced significant changes in discharge, sedimentation, and water quality. To date, however, erosion studies have been limited to examining the sediment yield in small basins (Chin, 2006). Few geospatial studies have applied historical datasets with high resolution imagery over multiple years to a single, large system (Graf, 2000). Thus, our fields continue to be challenged to quantify links between urban expansion, population growth, and channel morphology.

Systematic, large-scale observations of channel morphology are essential to evaluating human and/or urban impact on stream behavior (Marston *et al.*, 1995; Graf, 2000), but are difficult to obtain. For example, visual monitoring (e.g., aerial images) of large hydrologic systems is expensive and has, historically, lacked the temporal resolution required to capture trends over a period of decades. In addition, observation methods applied in most settings cannot adequately distinguish between changes to a

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hydrologic system caused by both natural processes and urban growth. Further complicating large-scale assessment, several researchers have suggested that channel changes associated with urban development depend largely on specific parameters of the system under study, such as geology, sediment distribution, and flow dynamics. (Chin, 2006; Kang and Marston, 2006; Poff *et al.*, 2006). Thus, generalizing methods and predictions from one system to another has been difficult at best.

In the face of the above challenges to large-scale monitoring, the Las Vegas Wash, Nevada, provides a unique setting in which to examine the impact of urban growth on a major hydrologic conduit for one of the fastest growing cities in the United States. The present channel system of Las Vegas Wash is not a natural system; its morphology has evolved as a result of urban growth. Prior to the late 20th century growth of the city of Las Vegas, the Wash was an ephemeral stream that only carried water after periodic rain storms; no streamflow occurred during dry periods (Glancy and Whitney, in press). The original floodplain existed as a gentle-sloping surface. In the early 20th century the then-small city of Las Vegas began discharging wastewater into Las Vegas Wash. By the 1950s, the growing urban area discharged enough wastewater into Las Vegas Wash to create a small, but perennial, streamflow. By 1999, the simple ephemeral stream had been transformed into an active river channel – almost 40-m wide – that emptied into Lake Mead. Increases in wastewater discharge and storm runoff are the only factors that have contributed to channel change in Las Vegas Wash (Glancy and Whitney, in press).

Given the unique history of the Las Vegas Wash, datasets from this region provide opportunities to review channel change as a function of increased discharge while holding other parameters constant. Using high-resolution aerial photographs taken in 1975, 1989, and 1999, the current study applies new spatial analysis techniques to characterize the influence of discharge increase (caused by urban development) on channel morphology. The combination of fast-paced urban growth, the existence of high-resolution historical aerial data, and the unique characteristics of the channel system provides a rare opportunity to examine hydrologic alterations along the principal hydrologic conduit that drains the expanding urban area.

Observations of physical dimensions (such as width and volume), combined with observations of vegetation and channel form, provide critical parameters with which to identify anthropogenic perturbations in natural drainages. Several studies have assessed basic channel change by using geospatial techniques, such as overlaying a series of historical channel maps (Downward *et al.*, 1994; Marston *et al.*, 1995; Gurnell, 1997). This sort of quantitative assessment of hydrologic alteration poses an array of challenges because historical datasets are time consuming to digitize and few datasets have sufficient temporal or spatial resolution to be useful (Graf, 2000). In addition, geospatial studies of channel morphology have largely been limited to examinations of alterations in channel form (e.g., width, shape, change of position). Estimates of sediment addition or removal from a system require digital elevation models (DEMs), which are expensive to create. Errors in ground-control point elevations, inadequate spatial distribution of ground-control points, or variation in interpolation methods can result in variations of elevation and therefore inaccuracies in erosion calculations.

The current study incorporates advancements in spatial analysis technology to address many of the limitations faced in previous research, thus offering the field new methods to quantify hydrologic system changes resulting from urban expansion. Specifically, we examined the channel morphology of Las Vegas Wash and calculated volumes of sediment removed from the system. Using a GIS, photosets of the wash were compared to delineate areas of channel change between each photoset. Time Period 1 compares the channel system captured in the 1975 photoset to the original surface prior to erosion. Time Period 2 identifies the channel changes between the 1975 and 1989 photosets. Finally, Time Period 3 maps the alterations between the 1989 images and the 1999 images. Volumes of sediment erosion were calculated to assess how erosion changed in response to population growth. The erosion calculation method applied, reduces the amount of error introduced by inaccuracies within DEMs.

STUDY AREA

The city of Las Vegas is located in a semi-arid basin in southeastern Nevada at an approximate elevation of 549 m. Las Vegas Valley is drained by the Lower Las Vegas Wash, a tributary stream of the Colorado River that now flows into Lake Mead. Before urbanization began in the early 20th century, Las Vegas Wash existed for 3,000 years as a typical semiarid, ephemeral stream, characterized by aggradation during infrequent floods (Glancy and Whitney, in press). Today, Las Vegas Wash begins in a broad valley that narrows and intersects several alluvium deposits before issuing into Lake Mead. The valley floor slopes gently to the southeast, dropping about 152 m in elevation, over about 20 km.

Since the 1980s, Las Vegas has been the fastest growing urban center in the United States. Not surprisingly, Las Vegas Wash has been considerably altered in the face of such dramatic urban expansion. Changes to the ephemeral stream began when wastewater effluent was discharged into Las Vegas Wash by a sewage treatment plant built in 1950. By 1955, perennial flow began in the Las Vegas Wash and the alluvial fill became saturated by excess water (Glancy and Whitney, in press). Initially, the increasing discharge transformed the vegetation from a floodplain (dominated by sparse desert shrubs and small patches of mesquite trees, willows, greasewood, and saltgrass) to several areas of thick marshlands with robust riparian communities.

Increases in discharge can be directly linked to increases in the urban population (Figure 1). Specifically, tourism visits began to rise steadily around World War II when developers created resorts and casinos. Increased tourism, in turn, attracted larger numbers of permanent residents to the area. Strikingly, the population nearly doubled between 1989 and 2000 (U.S. Census Bureau, 2000). Population and tourism increases affected Las Vegas Wash in at least two ways: increases in the discharge of treated sewage effluent and greater volumes of urban runoff from the growth of impervious surfaces. Less infiltration during storms in conjunction with increasing amounts of storm runoff contributed to an increase in stream power and erosion potential. Large volumes of sediment have been removed from Las Vegas Wash, which has resulted in a 12-year channel and floodplain reconstruction effort that will cost over US$125M (J. Whitney, unpublished data).

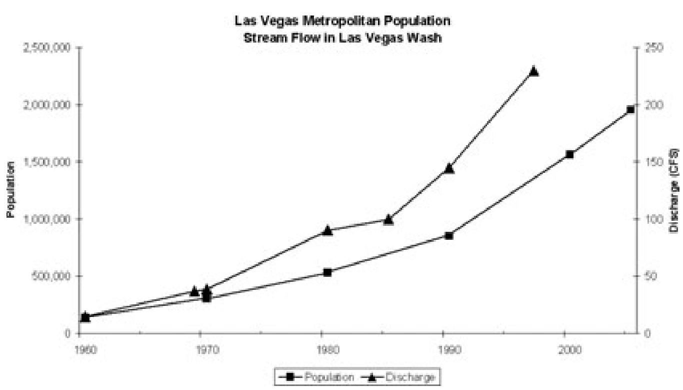

FIGURE 1. Comparison of Population Growth and Stream Discharge From 1960 to 2005.

METHOD

Method Overview

Three aerial photosets of 1975, 1989, and 1999 were processed for orthocorrection and georegistration to evaluate the channel changes and sediment erosion within Las Vegas Wash. In a GIS, active channels in each group were digitized, as well as the areas adjacent to the channels that had been altered by water since the prior image set. These results yielded three separate time periods in which the channel system had been modified from the original floodplain of the ephemeral stream. Each time period provided channel dimension changes, as well as a spatial footprint of the areas in which sediment was added or removed. The areas of change were overlaid with DEMs to calculate the total amount of sediment removed from the channel during each time period (Figure 2).

Image Processing

The 1975 and 1989 datasets of aerial photographs were scanned and georegistered to project them in a GIS. This process requires the selection of ground-control points that are defined in the software with specific coordinates.

The 1975 set consisted of 29 black and white orthocorrected images taken in March at a scale of 1:12,000. Each image was a 40 × 21.5 inch map sheet overlaid by place name labels, coordinates, and registration marks created by Teledyne Electronics (Thousand Oaks, CA). Southern Nevada Water Authority (SNWA) scanned these maps at 600 dpi and provided digital copies. The images were manipulated and cropped using Adobe Photoshop. Using Environmental Systems Research Institute (ESRI) Arc Workstation, each image was registered and rectified with an average root mean square (RMS) error of 0.44 ft. The original projection of the aerial photo had to be altered so that each dataset could overlay one another. To change the coordinate system, all images were converted into rasters, with each cell equaling 0.33 ft (10 cm).

The 1989 photoset consisted of 14-color, aerial photographs taken in September. Photos had an original scale of 1:6,970 and were scanned at 1,000 dpi. Camera reports were obtained from the pilot so that the fiducial marks could be used to register and rectify the images. This dataset presented a number of problems for converting the digital images to a GIS. Prior to September 1989, engineering work had begun to create a reservoir, Lake Las Vegas, between the Three Kids Wash and Las Vegas Bay (Figure 3). Lake Las Vegas now covers 0.63 km^2 and the former channel is now funneled under the lake through large concrete pipes. In addition, some terrain was dramatically altered, so that control points were difficult to find, especially on the eastern side of Las Vegas Wash. RMS errors were so high in some cases that images were rubber sheeted instead of

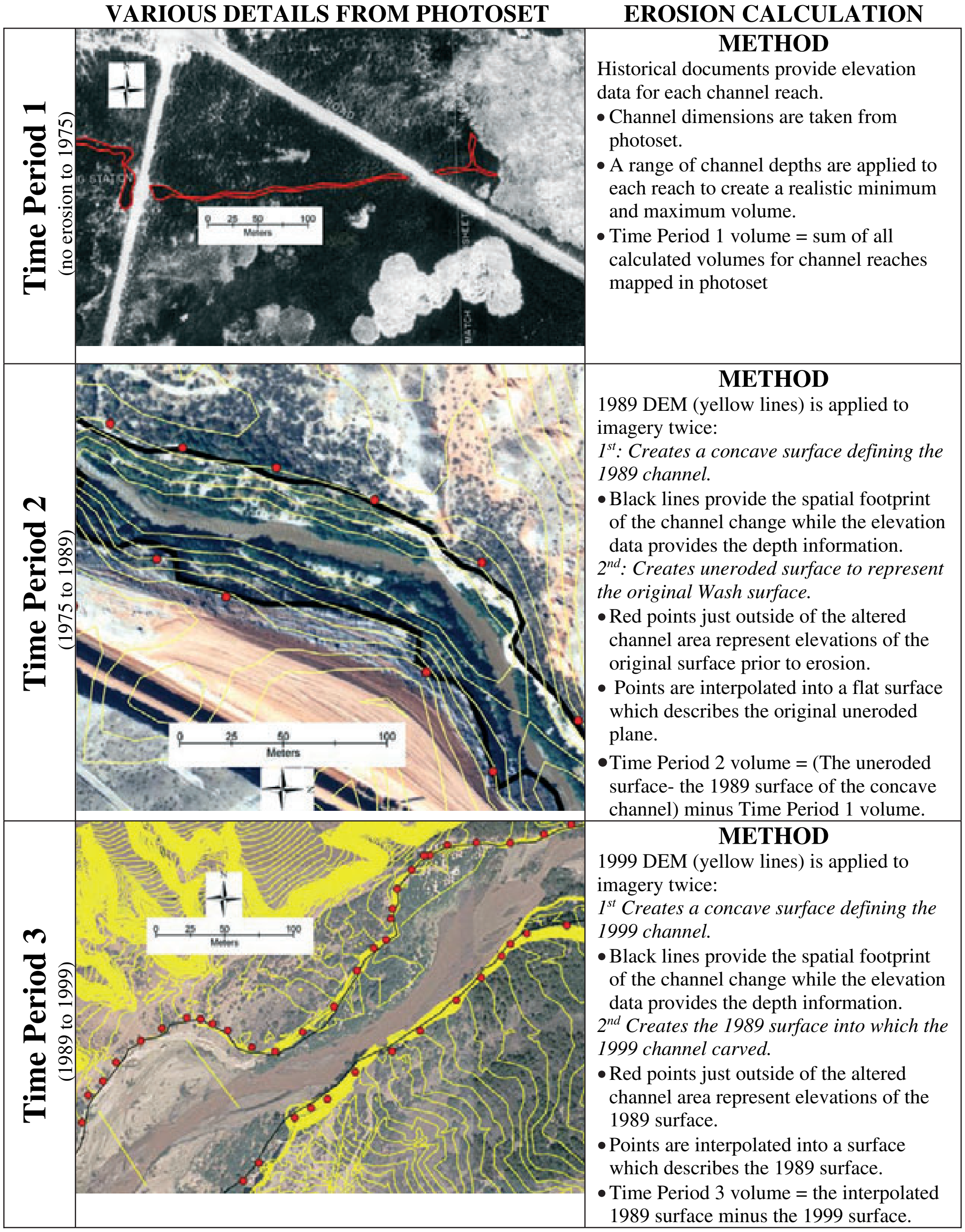

FIGURE 2. Summary of Erosion Calculation Methods.

orthorectified. Orthocorrection bends the photo so that distortions created by the camera vantage point are removed. Although not every image could be orthocorrected, the image centers were used to reduce error created by distortions in each photo. Rubber sheeting, or warping one photo to another, does not completely remove parallax error but does reduce it. Final cell size for most images was 0.34 ft (10 cm).

The 1999 aerial dataset required no processing as it was a completely rectified and registered dataset from the SNWA. Thirty-eight digital color images with 1-ft (0.3 m) pixels covered the entire area as well as outlying mountains and water-treatment facilities.

Channel Delineation

In each set of images, a series of polygons were drawn to describe the shape of the active channel. During the 24-year period of the study, the active channel shifted laterally across the valley floor, such

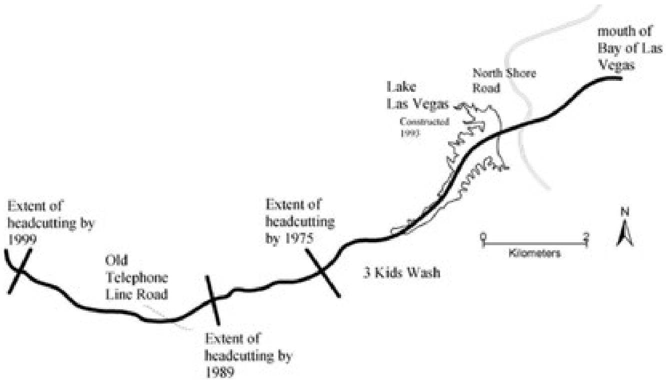

FIGURE 3. Plan View Map of Las Vegas Wash.

that the floodplain presented in one set of images did not necessarily reflect the floodplain area of the previous set of images. To capture the entire area that experienced hydrologic changes, two photosets were overlaid in a GIS. The GIS provided a tool to map all the areas adjacent to the active channel that experienced alteration. Mapping the areas of change detected between the two photosets created a spatial footprint of erosion.

Mapping areas of change between two datasets could not be automated and required manual mapping. In studies where one sensor or camera captures multitemporal images, change detection can often be computerized using a variety of different classification algorithms. In this study, each dataset was taken with a different camera type that captured different styles of images. Initial attempts to automate change detection were unsuccessful. A series of predefined rules were applied to each time series to identify and define the areas of change. For example, if a specific area showed dense vegetation in one dataset and partial vegetation in the subsequent photoset, then the area was designated an area of change. Areas where change occurred by means other than water (e.g., a road was constructed between datasets) were excluded. In this study, the term "floodplain" is used to refer to any area adjacent to the channel in which hydrologic alteration is visible.

GIS provides a robust set of tools for measuring and quantifying spatial dimensions; however, width is not easily measured with ESRI software. To measure channel width, an ARC Macro Language script was used called Polystats which is available on the Internet (http://www.fs.fed.us/digitalvisions/tools/index.php). The Polystats program calculates the minimum dimension of a rectangle that has the same perimeter and area as the polygon of interest. As the polygon curves approaches a circular shape, the square root of the area is used instead rather than rectangular dimensions.

Time Period 1: Preurbanization to 1975. The Time Period 1 dataset assumes that Las Vegas Wash was an ephemeral stream that only flowed as a consequence of storm runoff prior to development in Las Vegas. Little to no incision into the valley surface fill occurred prior to the construction of a wastewater treatment plant in 1950 that initiated the release of effluent into Las Vegas Wash (Glancy and Whitney, in press). Thus, the 1975 image set was compared to a flat surface representing the original floodplain without any significant incision. The incision mapped in Time Period 1, represents the total volume of material removed from prior to the initiation of wastewater discharge in 1950 to 1975 (Figure 2).

The 1975 photoset is composed of coarse black and white images; however, these images provided only the aerial view of the wash prior to extensive erosion. On some aerial photographs, water and bare ground were almost indistinguishable. In other areas, the active channel was covered by vegetation. In 1975, the main channel was narrow and incised channel segments were discontinuous. Most of the floodplain was covered by broad flat marshes. These issues – poor resolution, image quality and narrow channel widths – compromised the accuracy of the 1975 channel measurements. Therefore, the line work for this dataset only includes the visibly distinct active channels. Time period 1 represents a very conservative estimate of erosion from the prewastewater, flat floodplain to the 1975 incised floodplain.

Time Period 2: 1975-89. Unlike Time Period 1, two separate photosets were used to delineate the hydrologic changes between 1975 and 1989. By overlaying the 1975 aerial photos on those taken in 1989 (Figure 4), changes in the areas adjacent to the channel could be mapped with a series of polygons describing the spatial footprint of the floodplain between the two photosets. Areas that appeared eroded or regularly inundated were mapped, while areas on the valley floor that were unaltered were left outside the floodplain borders. Typically, differences in land surface patterns were used to identify floodplain boundaries. Channel incision, changes in vegetation composition or density, as well as changes in slope or aspect, were interpreted as signs of hydrologic alteration (Figure 4). In the 14 years during Time Period 2, significant development-related changes had taken place in the wash, including road building, pipeline construction, and preliminary construction of Lake Las Vegas (Figure 3). As observed in the previous Time Period, surface alterations that resulted from other processes than hydrologic (e.g., road building, bulldozing) were excluded. To produce a conservative estimate of volume of material removed in the channel, areas were also excluded that appeared to have

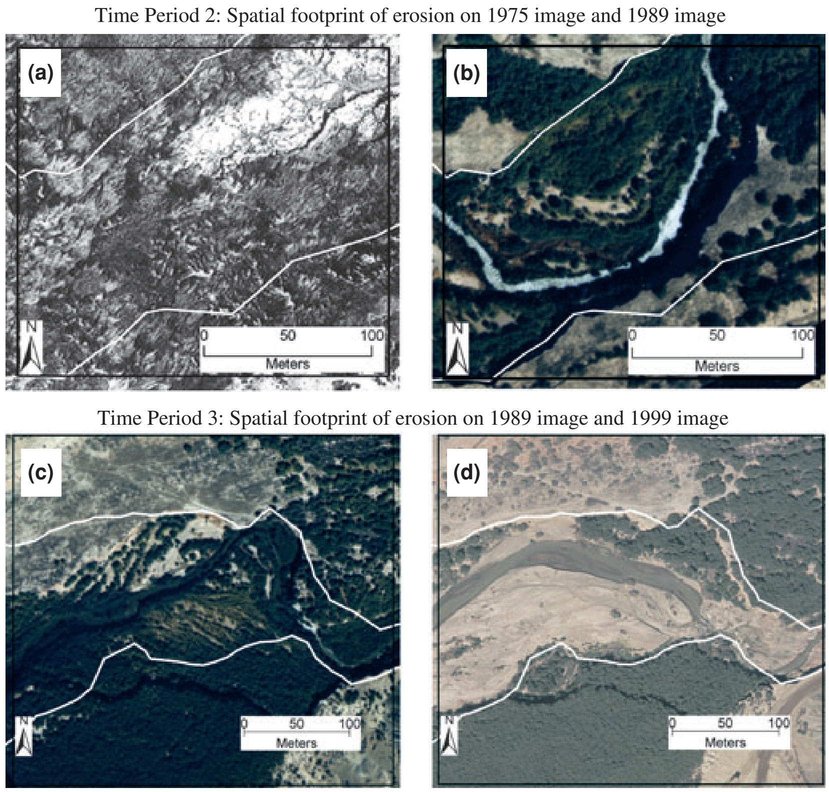

FIGURE 4. Image A: Photo of the 1975 Channel With Time Period 2 Polygons of Hydrologic Change Detection. Image B, photo of the 1989 channel with the Time Period 2 line work showing active channel and floodplain. Image C: photo of the 1989 channel with Time Period 3 line work showing polygons of hydrologic change detection. Image D: photo of the 1999 channel with the Time Period 3 lines work showing active channel and floodplain.

been degraded by combinations of hydrologic and construction disturbances.

Time Period 3: 1989-99. Time Period 3 was constructed using the same rules to identify hydrologic changes in Time Period 2. Photosets from 1989 were over laid by 1999 images (Figure 4). All areas showing hydrologic changes were mapped by polygons, while areas that showed no change were excluded. In the upstream portion of Las Vegas Wash, flood scouring may have incised the surface approximately 0.5 m beyond the mapped polygons. Shallow incision in vegetated reaches was difficult to visually discern. One of the general mapping rules used in this study required that if the photos did not show evidence of change visually, even if change could be reasonably inferred, those areas were not included as areas of change.

Surface Generation

No surface was created for the Time Period 1 sediment volume calculation. The most accurate elevation information in 1975 was provided by engineering data in the form of channel reach length and depth. No DEM was available. Thus, rather than constructing a virtual surface, historical measurements (Glancy and Whitney, in press) provided dimensions for volume of material removed from an uneroded surface (Figure 2).

Virtual surfaces represent a continuous surface of elevation and create three-dimensional forms for the channels and altered floodplains. Generally, a surface can be created by converting topographic contours into rasters. SNWA provided a complete set of 1-ft (0.3 m) contour lines derived from the 1999 photoset; these were then converted into a raster using the Topogrid algorithm in Arc Workstation. The 1989 surface was generated by orthophotos taken in 1989 and 1990. Ten-foot (3 m) contours are available on the Clark County GIS website (http://gisgate.co.clark.nv.us/gismo/gismo.htm). However, the contour set did not completely cover the study area. There were two sections of missing data: (1) a small area just west of Three Kids Wash and (2) a area just east of North Shore Road (Figure 3).

A variety of methods were used to complete the 1989 surface, including incorporation of additional data points and photo interpretation. First, all areas of missing data were converted to "no data" values in the raster. Second, the 1999 values supplanted the "no data" values such that unaltered 1999 data filled in some of the missing area in the 1989 DEM. The remaining holes in the 1989 DEM were filled by photo interpretation of the 1989 dataset. The 1989 photos provided data to build a contour set which was later converted into a raster and combined with the 1989 DEM. This surface was then analyzed for errors by mapping the standard deviation of the interpolated data.

Erosion Calculation Methods

Many studies that calculate erosion use raster mathematics to calculate volume changes (DeRose *et al.*, 1998; Betts and DeRose, 1999; Lane *et al.*, 2003). Essentially this method subtracts a younger surface from an older surface. For example, as shown in Figure 5, a historic surface that has a target pixel with an elevation of 1,457 m overlies a younger surface with a pixel elevation of 1,455 m, which indicates that pixel has lost 2 m of material. Importantly, this calculation approach assumes that both DEMs have a similar error value or a systematic error. Often, though, historical DEMs are created from control points on topographic maps that can have significant vertical errors, as great as 3 m. In the case of the sample pixel in Figure 5, the error variance exceeds the difference generated between the two surfaces. Several researchers have dealt with these problems by analyzing the standard deviation of each surface to estimate a systematic error factor (Lane *et al.*, 2003). In the current study, the variance in the surfaces values was not systematic; therefore, a single error correction factor could not be applied to one surface.

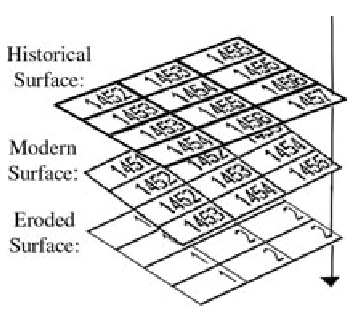

FIGURE 5. Illustrates the Common Method Calculate Erosion Using Two Metric Digital Elevation Models (DEMs).

Alternatively, we applied a method to calculate erosion volumes by calculating the volume of each channel. By using a single DEM, errors between surfaces are not included in the calculation. Two separate surfaces were generated from a DEM (Figure 2). First, the DEM was applied to the spatial footprint of erosion derived from the GIS analysis, which defined the boundary of the concave channel for each time period. The same DEM was used again to construct a second surface which represented the original surface elevations prior to the erosion. For example, Figure 6 shows the 1999 channel eroded into the 1989 surface. The spatial footprint or "floodplain," outlined in yellow, characterizes where Time Period 3 incision occurred. The geometry of the floodplain is simple enough so that the elevation of the 1989 surface can be described by points just outside the floodplain. To create the 1989 surface, points just outside the floodplain (red points in Figures 2 and 6) all along the Las Vegas Wash were selected from the 1999 DEM and converted into a shapefile. These elevation points were interpolated into a flat surface describing the 1989 surface into which Time Period 3 erosion took place (Figures 2 and 6). Therefore, the surface described by Time Period 3 was subtracted from the surface interpolated as the 1989 surface. By using only one DEM, the calculations exclude elevation errors and retain the relative volume of the material removed. Two different DEMs were used for the Time Period 2 erosion calculation and Time Period 3 erosion calculation (Figure 2).

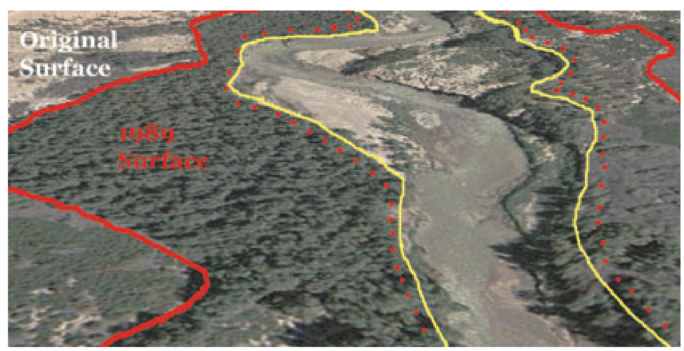

FIGURE 6. An Oblique Image of the 1999 Las Vegas Wash Surface Illustrates How Two Surfaces Could Be Generated From a Single Digital Elevation Model (DEM). The red dots indicate elevation points of 1989 surface. Interpolation creates a flat surface between these points into which the Time Period 3 channel erodes.

RESULTS

Channel Morphology

Changes in channel morphology were documented in this study by mapping the variations between photosets. Table 1 compares the spatial relationships of the channel change by summarizing the width of the active channel, the "floodplain" (areas adjacent to the channel having experienced hydrologic alteration), and the combination of the two as the width of the

TABLE 1. Las Vegas Wash Channel Widths 1975-1999.

		Time Period 2			Time Period 3		
	Time Period 1 (m)	**Downstream (m)**	**Upstream (m)**	**Total Surface Alteration (m)**	**Downstream (m)**	**Upstream (m)**	**Total Surface Alteration (m)**
Average* active channel width	3	12	6	10	48	33	37
Average* floodplain** width	0	24	132	109	22	52	45
Average* total surface alteration***	3	36	138	119	71	85	82

*Averages are based on percentage of total area.
**"Floodplain" refers to borders of the active channel that have experienced hydrologic alteration.
***"Total surface alterations" combine the widths of the active channel and the defined floodplain.

total surface alteration. Channel dimensions were segmented into upstream and downstream portions to capture the progression of channel changes upstream during the 24-year period.

In Time Period 1, little incision into the valley fill occurred. The stream system was composed of separate discontinuous, shallow, and narrow channels connected by marshes. Only modest amounts of erosion resulted from headward cutting gullies. Time Period 2 describes a different hydrologic system where the channel became continuous and was no longer segmented by marshes. The active channel widened to 10 m. Floodplains (areas of change adjacent to the channel) exceeded an average width of 100 m. The upstream channel and floodplain became substantially wider than the downstream section, likely because runoff in the lower Las Vegas Wash was concentrated in deeper channels (former discontinuous headcuts). This picture suggests bankfull events occurred upstream more frequently than downstream. In Time Period 2, the active channel in the downsteam portion is 12 m wide, suggesting the wider channel was more efficient in carrying larger discharge events.

During Time Period 3, additional changes to the channel system are recorded by variations in width. The Time Period 3 active channel is almost four times as wide as that of Time Period 2. However, Time Period 3 floodplains are, on average, only half the width of those in Time Period 2. The reduction in floodplain width in Time Period 3, especially upstream, suggests that bankfull events were either less intense and/or incision deepened the channel to make bankfull events less frequent. The increase in active channel width occurred in response to continued increases in wastewater discharge entering the channel and suggests that the erosion capability of the channel increased from Time Period 2.

Erosion Estimates

Erosion calculations approximate the amount of material removed from the system in Time Periods 1, 2, and 3 (Table 2 and Figure 2). Time 1 calculation is based on historical data available from 1975. There are a number of resolution issues and spatial inconsistencies within this dataset; therefore, a range of depths values was assigned for each channel reach (typically 1.2-1.8 m or 4-6 ft). This form of calculation provided a reasonable minimum and maximum for eroded material for the 1975 channel. The final results for Time Period 1 indicate that 84,000-127,000 m^3 (Table 2) of material had been removed from the ideal surface of the valley bottom. Roughly 1-2% of the total eroded volume was removed by 1975 through discontinuous gullies.

TABLE 2. Las Vegas Wash Erosion Calculations.

	Volume (m^3)	**Percentage of Total**
Time Period (1989-99)		
Downstream	442,000	6.71
Upstream	2,633,000	39.97
Total	3,075,000	46.68
Time Period 2 (1975-89)		
Maximum	3,429,000	52.05
Minimum	3,386,000	51.40
Time Period 1 (<1975)		
Maximum	127,000	1.27
Minimum	84,000	1.92
Total volume removed	6,588,000	

The resolution of the 1989 images provided enough spatial information to map out the footprint of the channel and the areas adjacent to the channel that had been altered since 1975. The final calculation of sediment volume removed in Time Period 2 included the amount of material removed from the ideal valley surface minus the range of volumes calculated in Time 1 (Figure 2). Our results indicate that 3,429,000-3,386,000 m^3 or roughly 51% of the total volume was removed by 1989.

Calculations for Time 3 were divided into downstream and upstream sections as a result of the construction of Lake Las Vegas in 1990. The downstream section includes the valley from Lake Las Vegas to the head of the delta in Las Vegas Bay (Figure 3). The upstream section includes the valley from Three Kids

Wash to western-most evidence of channel erosion. The calculated total sediment volume removed in Time Period 3 is 3,075,000 m^3. This represents 46% of the total volume removed across the 24-year period, and 85% of the Time Period 3 volume was removed from the channel upstream of Lake Las Vegas.

DISCUSSION

Wastewater and storm events caused profound channel changes in the Wash from 1975 to 1999. It is beyond the limits of this study to estimate the specific contribution of either wastewater or storm runoff; however, these results reconstruct the evolution of the channel system in response to increasing amounts of discharge. Table 3 summarizes variations in hydrologic conditions during Time Periods 1-3. Time Period 1 conditions show stable channel conditions as evidenced by the presence of thin discontinuous channels, marshes and thick riparian areas, and modest amounts of erosion. Large storms between 1950 and 1975 did not cause massive erosion, likely because runoff soaked into soils preventing large quantities of water from being quickly funneled toward the channel. In contrast, Time Period 2 conditions suggest a system struggling to adjust to increases in effluent discharge and storm runoff. Both population and discharge rapidly increased (Figure 1). In the face of increased wastewater release, the active channel width in Time Period 2 increased to *3 times* the width of the previous time period. Broad floodplains (143 m wide) in the upstream channel characterized rapid flood events (Table 3). Incision in some areas exceeded 7 m. Extensive development of impervious surfaces likely accelerated the rate in which storm runoff reached the channel system. Yet in the photographs, scour and incision were not easily noticed. The vegetation was dense, except for a few patchy areas near cut banks. The presence of several abandoned oxbow channels implied low levels of stream power and suggested perhaps storms events may have reduced the natural sinuosity of the channel. Increased storm runoff caused severe erosion, particularly during an intense series of eight storms in 1984; however, significant storm events were infrequent enough that the channel system could stabilize between events.

Channel system changes in Time Period 3 indicate that the system was unable to stabilize in response to increased discharge. The width of the active channel expanded dramatically. The decrease in floodplain width suggests that incision may have compensated for floodplain width during flood events (Table 3). Relative to Time Period 2, flood events were not as extensive in Time Period 3 because: (1) the magnitude of the events were smaller or (2) incision was rapid enough to reduce the lateral expansion of the floodplains. Characteristics of destabilized banks with large denuded point bars and midchannel islands signify the channel bed load is regularly in motion. A thick riparian community was replaced by small patches of vegetation, including islands of plants in the floodplain. As the population in Las Vegas grew, wastewater discharge increased at the same rate. Figure 1 shows a distinct slope change in discharge in beginning in 1989 that can be attributed to a surge in population. The channel system in Time Period 3 was also shorter than that of Time Period 2, as the entire area of Lake Las Vegas was excluded from Time Period 3 (Figure 3). Although the erosion calculations for Time Periods 2 and 3 are similar, the erosion in Time Period 3 takes place in only 10 years and over a shorter channel length than in Time Period 2. These observations, taken together, suggest that the erosion accelerated in Time Period 3.

Estimating Error in Sediment Loss Calculations

The errors in sediment loss calculations are specific to each dataset; thus, a study-wide error value cannot

TABLE 3. Channel Characteristics of Las Vegas Wash 1975-1999.

	Average Active Width (m)	Average Floodplain Width (m)	Volume of Sediment Removed (m^3)	Volume of Sediment Removed per Year (m^3)	Vegetation Adjacent to Channel	Channel Characteristics
Time Period 1	3	0	105,500	4,220	Dense including extensive marshes	Discontinuous with little sinuosity
Time Period 2	10	109	3,407,500	243,393	Uniformly dense with cut banks of patchy vegetation	Continuous, evidence of oxbow channels
Time Period 3	37	45	3,075,000	307,500	Benchs of dense vegetation cropped by stream incision, large interstitial spaces between plants	Continuous with denuded point bars, midchannel islands

be specified. While each calculated volume represents the most accurate data available for that time period, the lack of a study-wide error estimate is inherent to projects that apply diverse datasets collected over extensive time periods. For example, Time Period 1 may include three small areas of the wash that may have been channelized, although that is not visible in the photoset. If those areas were included to the erosion calculations, Time Period 1 erosion volume might be as much as be 6% larger than the number calculated in this study. This potential error would then reduce the volume of the Time Period 2 sediment loss. However, such a large difference between the volumes calculated in Time Periods 1 and 2 suggests that any bias in calculation would be negligible.

Biases in the Time Period 2 calculation could be more extensive than Time Period 1, because some elevation values were estimated based on photo interpretation. These errors would increase Time Period 3 erosion values and decrease Time Period 2 erosion estimates. Biases in the Time Period 3 calculations are limited to the accuracy of the elevation model, which is 6 cm. If estimates of the 1989 surface used in the Time Period 3 calculation were incorrect by 1 foot across the study area, the difference in volume would be negligible (<3% of the total calculated in Time Period 3).

In spite of possible biases in calculations at the three time periods, the total erosion volume estimated here converges with two studies of sediment deposited into Las Vegas Bay of Lake Mead. Side-scan sonar imagery and seismic-reflection profiles collected by Twichell *et al.* (1999, 2001) resulted in an estimate that 5.7 Mm^3 of sediment accumulated in Las Vegas Bay after completion of Hoover Dam. The GIS calculation of 6.6 Mm^3 (Table 2) is approximately 24% greater than the volume calculated by Twichell *et al.* (2001). The difference between the volumes is partly a function of the mapping methods. The Twichell study could only assess submerged sediment. Lake levels in Lake Mead fell while the delta at the mouth of the Las Vegas Wash grew. The sonar study excluded all material above lake level. A second study (A. Ehrenburg, unpublished data) used a 3D modeling program to assess the volume of the delta prograding into Las Vegas Bay. By subtracting a 2001 topographic contour dataset of the exposed delta from a 1930s set of topographic lines created for the construction of the Hoover Dam, a delta volume of 6.3 m^3 was calculated. Although this volume is within 4% of the calculated volume in this study, the deltaic study excludes sediments carried out beyond the delta and deposited farther in Lake Mead. The estimated delta volume also includes error problems described earlier using two separate DEMs.

For several reasons, biases in volume estimates are most likely to underestimate the overall volume of sediment eroded from Las Vegas Wash. First, when problems were encountered in calculations, the most conservative volumetric estimate was always used. Second, Time Period 1 volume is limited to only the incision that was visible in the photoset; Time Period 2 volume was limited by the surfaces captured in the dataset. Additional incision may have been mapped if additional photos had been taken further upstream in Las Vegas Wash. Third, in both Time Periods 2 and 3, several localities were excluded because alterations may have included nonhydrologic processes (e.g., construction).

CONCLUSION

Las Vegas Wash offers a unique example of the hydrologic changes that can occur in response to urban development in a semiarid basin. The GIS methodology employed in this study reveals striking links between urban expansion in Las Vegas, Nevada and channel changes, including significant erosion, from 1975 to 1999. The spatial methods applied here offer insights into how natural systems may respond to rapid urban changes.

In addition, the method used to calculate erosion improves upon earlier modeling techniques. Erosion calculations are a conservative estimate of sediment eroded from Las Vegas Wash and are not inflated by errors propagated by the use of multiple DEMs. The use of one DEM to create two surfaces to measure erosion allows for the final calculation to be a relative volume estimate tied to the accuracy of the single DEM.

The results produced by the spatial analysis suggest the hydrologic history of Las Vegas Wash is dominated by three hydrologic conditions. Small additions of clear wastewater effluent in Time Period 1 (pre-1975) result in the development of marshes connected by narrow channels 3 m wide. A small amount of erosion occurred (just over 100,000 m^3) during the growths of several headcuts. Those conditions changed in Time Period 2 (1975-89) because wastewater and storm runoff into the valley increased as the physical city of Las Vegas expanded with acres of impermeable surfaces. In Time Period 3 (1989-99), a sharp increase in wastewater discharge is associated with an acceleration of erosion in the valley. More than 3 Mm^3 of material were removed from the channel during a 10 year period whereas a similar amount occurred in the previous time period covering 14 years. The total volume of sediment removed from

Las Vegas Wash, about 6.6 Mm^3 during urban expansion in the late 20th century, is the largest documented volume of sediment that can be attributed to the effects of urbanization.

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